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FUNDAMENTAL PRINCIPLES OF COHERENT-FEEDBACK QUANTUM CONTROL

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We have performed three years of research on fundamental principles and potential applications of coherent-feedback quantum control, with primary focus on optical metrology and photonic/nano-optomechanical information processing platforms. Major results include the formulation and analysis of coherent-feedback cooling schemes for optomechanical oscillators,

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During the three-year performance period we have carried out a program of theoretical research on the foundations and potential applications of coherent-feedback quantum control. We have focused on potential applications in quantum-enhanced metrology and information processing, and on hardware platforms of an optical or opto-mechanical nature. The studies we have been performing begin to build a picture of how coherent feedback can provide a kind of circuit/network theory for quantum engineering, enabling rigorous analysis and numerical simulation of advanced devices and systems. We have begun to establish analytical approaches for comparing the performance of quantum-enhanced feedback control systems with classical counterparts, leveraging canonical results from classical control theory together with advanced methods for numerical simulations of proposed quantum systems. All of our results point to the interest of continued future study in this area, and of future investments in the experimental realization of the kinds of systems we propose.

In the published manuscripts “Advantages of Coherent Feedback for Cooling Quantum Oscillators" and "Coherent controllers for optical-feedback cooling of quantum oscillators," we have proposed and analyzed a class of feedback controllers for cooling mechanical oscillators to below ambient temperature. We specifically make use of coherent-feedback quantum control, analyzing feasible extensions of the kinds of optical probe setups already used in commercial atomic force microscopes. We first utilize the Linear-Quadratic-Gaussian results of classical stochastic control theory to establish limits for the best possible cooling (lowest steady-state effective oscillator temperature) that can be achieved using classical measurement-feedback control techniques, and then use computational optimization to discover coherent-feedback controller designs that surpass these classical limits by orders of magnitude. In metrological scenarios such as acceleration/vibration sensing using nano-electromechanical sensors, such improved cooling performance would translate directly into lower detection noise floors. In future work we plan to investigate the use of coherent cooling on pairs or eve networks of opto-mechanical oscillators to cool common-mode or differential modes of motion, which could be applied for quantum enhancement of the performance of phased accelerometer arrays.

In the published manuscript "Squeezed light in an optical parametric oscillator network with coherent feedback control” we describe an experiment we performed to demonstrate the use of coherent feedback to tailor the spectral properties of squeezed light. Squeezed light is currently of strategic interest for potential applications in metrology (acceleration sensing, vibrometry, gravity wave detection) and in quantum information processing (continuous-variables quantum cryptography). We specifically designed and constructed a network with two optical parametric oscillators, one of which serves as the “plant” and the other as the “controller” in a coherent feedback quantum control loop. By adjusting the parameters of the controller it is possible to improve the maximum degree of squeezing that can be achieved and to modify the spectral distribution of squeezing in unusual ways. The most notable achievement in spectrum tailoring was to move the maximum of squeezing off of the spectral line center, which had not previously been demonstrated but would be directly useful for measurement or communication schemes involving modulation sidebands (such as rf photonics). In future work we would like to investigate experimental coherent feedback networks involving highly nonlinear elements such as cavity QED devices, and networks driven by ultrafast pulsed lasers.

In the published manuscripts "Transformation of Quantum Photonic Circuit Models by Term Rewriting" and "Gauge subsystems, separability and robustness in autonomous quantum memories" we have continued our group’s long-term research program in the architectural principles of autonomous quantum information processing and on computer-aided design and modeling of complex quantum networks. Specifically, we showed in the first manuscript how term rewriting and other methods of computer-automated design can be adapted from classical hardware synthesis to the realm of quantum circuit engineering. As part of that study we also introduced an important new metric for the performance of a quantum memory that generalizes the usual notion of fidelity, to take into account the fact that correctable errors are generally only corrected after a short time delay in realistic quantum memory models. In the second manuscript we show how algebraic features of a subsystem quantum error correcting code make it possible to find planar layouts for a photonic circuit implementation that is much more robust to propagation losses of syndrome measurement beams than would be achieved by a naïve layout. We also investigate the importance of the separability of a quantum error correcting code for the existence of efficient planar circuit layouts. These two discoveries suggest a vastly different way of looking at quantum error correcting codes than has been popular in the field to-date. In a sense, we have shown that physical considerations about the possibility of efficient implementation of a code point to very different codes as “best” than do purely information-theoretic criteria such as distance or code size-to-capacity ratio. Whereas the fields of quantum information theory and quantum computer science might be considered to be at a somewhat advanced stage, our research shows that we are still just starting to develop a corresponding field of quantum circuit engineering.

The work we have done in the design and analysis of coherent-feedback circuits/networks impacts both quantum engineering and more near-term efforts in ultra-low power photonic signal processing. Both of these technology areas are important for AFOSR priorities in sensor networks, optical communication and avionics. While advancing the state-of-the-art in fundamental research in control of physical systems, we have also worked to make our methods accessible to engineers through our “QNET” suite of software tools available freely from GitHub. Between our publications and software distribution we hope that our work under this award can have a broad impact on continuing basic and applied research.

Five Stanford University Ph.D. students have performed significant parts of their thesis work under this award – Orion Crisafulli, Ryan Hamerly, Dmitri Pavlichin, Gopal Sarma and Nikolas Tezak.